Abandoned Coal Mine Methane Offset Protocol

Background Information on Performance Standard and Additionality

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Prepared by:

Ruby Canyon Engineering, Inc.

Abandoned Mine Methane (AMM) Background

In 2011, approximately 645 abandoned underground coal mines emitted an estimated 12 billion cubic feet (Bcf) of methane to the atmosphere, representing 7% of total U.S. coal mine methane greenhouse gas (GHG) emissions (~5 million metric tons CO2e). These figures do not include six Bcf of methane currently recovered from abandoned mines. Methane emissions from abandoned mines are estimated by the U.S. Environmental Protection Agency (EPA) for those abandoned mines that were considered "gassy" when active. A gassy mine is defined as emitting over 100,000 cubic feet of methane per day through ventilation and gas drainage systems. The EPA has identified approximately 500 gassy abandoned mines that have been closed since 1972, the earliest date that the Mine Safety Health Administration (MSHA) kept comprehensive records. In addition, the EPA has included 145 additional abandoned mines that were closed prior to 1972 based on historical mine records showing methane-related safety issues. These older mines represent approximately 20% of AMM emissions estimates. All of the gassy abandoned underground coal mines are located in 14 states1.

Sealing Mines

Entries to underground mines are typically sealed by filling shafts or portals with a porous fill such as gravel and capping the surface with a concrete seal. Vent pipes and boreholes are usually plugged in a similar manner to oil and gas wells; however, in years past many vent pipes were simply cut off and abandoned, thus allowing methane to vent to the atmosphere. Often times after a coal mine is abandoned and surface reclamation completed, coal leases revert back to the original lease holders which can be multiple owners based on surface land ownership. In these cases, responsibility for methane migration issues can be unclear.

Once a mine is closed or abandoned, the mine's methane gas production decreases, but methane liberation does not stop immediately. Following an initial decline, abandoned mines liberate methane at a near-steady rate over an extended period of time. The methane migrates up through conduits, particularly if they have not been sealed adequately. In addition, evidence has shown that diffuse emissions can occur when methane migrates to the surface through cracks and fissures in the strata overlying the coal mine.

Flooded Mines

After they are abandoned, some mines may flood as a result of intrusion of groundwater or surface water into the mine workings. The EPA estimates that flooded mines typically produce methane for only about 15 years following abandonment; unlike non-flooded mines that can emit methane for decades. Unless it poses an environmental risk, very little water monitoring data exist with state agencies regarding mine flooding.

In some cases where water contaminated by mining (acid mine drainage) is being mitigated, states require certain abandoned mines to maintain open pipes from the mine workings to direct water discharge. Methane is often emitted along with the water discharge.

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[1] Alabama, Colorado, Illinois, Indiana, Kentucky, Maryland, New Mexico, Ohio, Oklahoma, Pennsylvania, Tennessee, Utah, Virginia, and West Virginia

AMM Emissions Trend

AMM emissions are both a function of the active mine emissions prior to closure and the length of time since abandonment. AMM emissions peaked in the U.S. in 1998 following the closure of a large number of gassy mines in the 1990s. Methane recovery peaked in 2008, as two larges gassy mines with methane recovery and use systems closed in 2005 and 2008. **Figure 1** shows that since 2008, both methane emissions and recovery have been declining. However, any increase in the closure rate of coal mines due to current or future coal markets can cause AMM emissions to reverse the trend and increase.
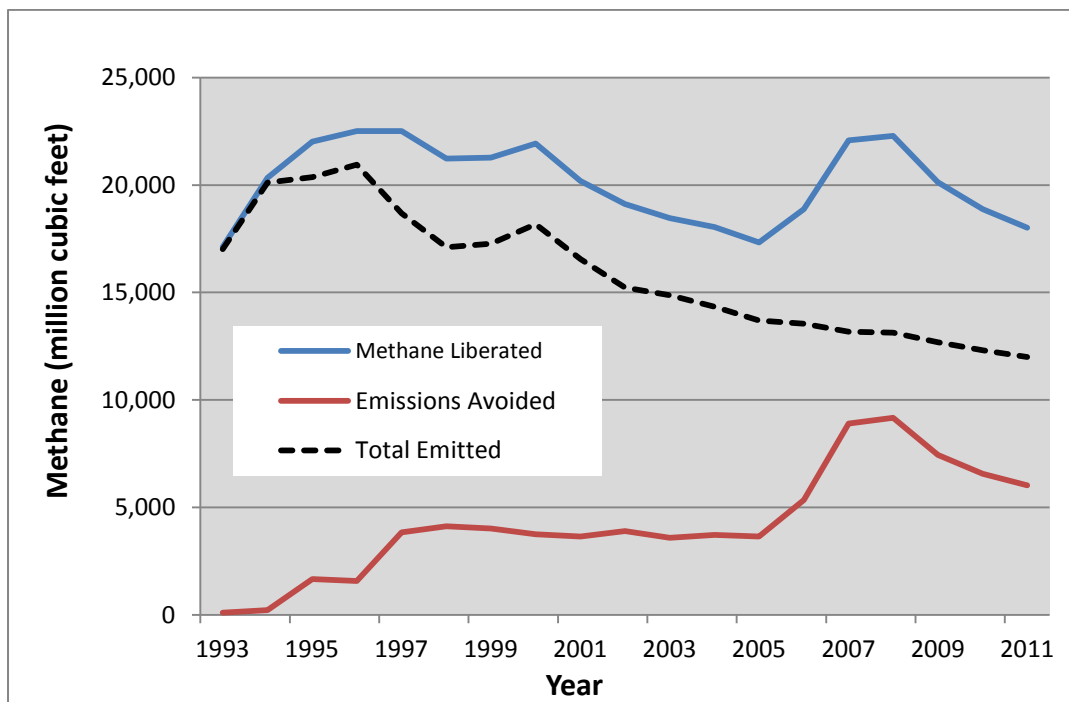

Figure 1: AMM Emissions Trend

Determining the Vertical Extent of Eligible AMM Wells

The vertical extent of a mine is less precise that the areal extent because of the effect of coal removal. In most U.S. coal mines roadways are built by removing the coal and other rock in order to move men and equipment throughout the mine. These road ways are generally a fixed height. However where coal is removed through pulling (removing) pillars in a room and pillar (also known as board and pillar) mine or through longwall mining, which removes all of the coal in a large panel, roof collapse causes significant fracturing in the strata above the mine coal seam and may even cause subsidence of the surface. These fractures can be a pathway for diffuse methane emissions from the mine to the atmosphere and they can also connect gas bearing zones above the mined seam to mine void. Consistent with accepted underground coal mine methane protocols, fracturing extends up to 160 meters above the mined seam and up to 40 meters below the mined seam (related to heaving of the floor as the stress of the overburden is removed). This fractured zone is known as the gob (also known as goaf).

In active gassy mines in the U.S. it is common for wells to be drilled and completed above the seam to be mined such that after the coal is removed and the and gob forms the methane released from the fractured gas bearing strata can be captured and vented at the surface (or utilized) before it enters the active mine workings producing hazardous working conditions.

Basis for Decline Curve Approach

For a more complete discussion of this approach please see "Methane Emissions from Abandoned Coal Mines in The United States: Emission Inventory Methodology and 1990-2002 Emissions Estimates" which can be found at:

http://www.epa.gov/cmop/docs/amm_final_report.pdf

To forecast methane emissions over time for a given mine, one must characterize the gas production of that mine as a function of time (e.g., a decline function), initiated at the time of abandonment. To accomplish this, EPA has used an oil and gas industry standard computational fluid dynamics (CFD) flow simulation model.

To illustrate how a decline curve can be built with the CFD[2] simulator, a conceptual model of a non-flooding, actively venting mine was built. The numerical model shown in **Figure 2** below was configured as a single well radial model with the wellbore placed in the center of the mined-out area, or void volume. The remaining volume was coal in communication with the void volume. This coal represents both the coal remaining in the mined seam and un-mined coal seams in communication with the void volume because of roof and floor fracturing and relaxation.

The model was configured to simulate a single component (methane), single-phase (gas) system with a runtime period of 100 years. The model was initialized at 20 psia in the void with the outer boundaries acting as barriers to flow. The void permeability was set very high to approximate the essentially free flow of the gas through the mine void. The coal permeability was set at a value based on the coal basin of interest, as was adsorption isotherm used to model methane desorption from the coal. The minimum pressure was limited to one atmosphere.

According to this model, the gas from the mine void depletes rapidly, reducing the methane pressure in the mine, which in turn allows desorption of methane from the coal. This methane then migrates to the void area where it is removed from the system. In generating the family of dimensionless emission decline curves, the conceptual model size was held constant and the methane flow capacity was modified by adjusting the permeability.

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[2] CFD software uses the rate equations of gas flowing through a porous media (conservation of momentum) with material balance equations (conservation of mass) in combination with an initial pressure and boundary conditions that define the flow geometry.
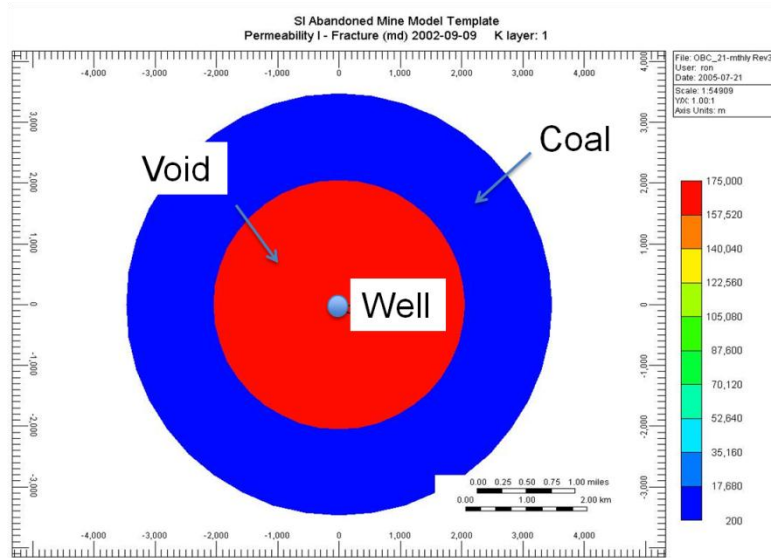
Figure 2: AMM Model Template

Venting Mines

At some abandoned mines, vent pipes relieve the buildup of pressure resulting from desorption and flow of methane into the mine void. These vents are installed to prevent methane from migrating into surrounding strata or through fissures in the earth into surface structures. An abandoned mine with an open (or "active") vent will behave very much like a natural gas well (at a much lower pressure regime).

Methane emissions from venting mines are a function of the pressure differential between the vent and the gas in the void and coal bed. The surface opening of the vent is at atmospheric pressure, while the gas within the un-mined coal seam near the mine void will range from atmospheric pressure (14.7 psi, or 1.01 bars) to tens of psi (more than 1 bar) above atmospheric pressure. **Figure 3** is an example emission profile for an abandoned mine over time.
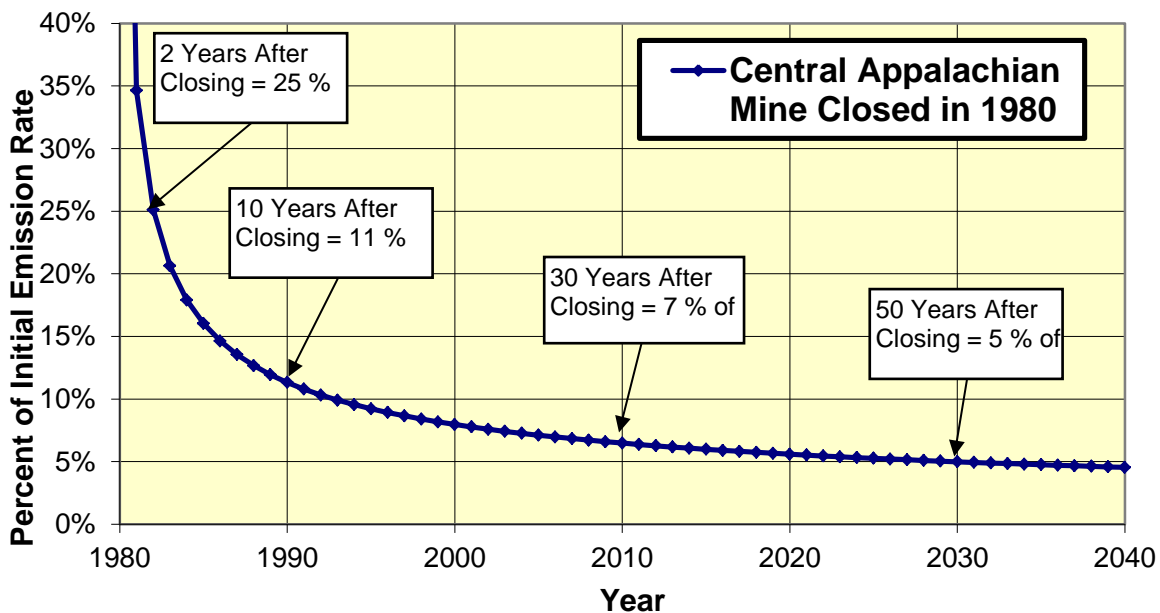
Figure 3: AMM Emission Rate

Sealed Mines

While many abandoned mines have active vents, some mines are sealed in an attempt to prevent unauthorized access or the escape of methane gas. Old shafts and drifts are commonly plugged with cement.

It is common, however, for gas to leak out around these plugs or to make its way through fractures in the overlying strata. The seals are generally assumed to leak even at very low pressure differentials (e.g., a few tenths of a psi), and they typically degrade over time. Although mine seals can impact the rate of flow, they are not considered to be effective at preventing atmospheric methane emissions over time.

Venting and Sealed Mine Decline Curves

The numerical output from the conceptual model was fitted to a hyperbolic decline function for ease of use.

$$q = qi(1+bDit)^{(-1/b)}$$

Where:

q = the gas rate at time t in mcf/d

qi = the initial gas rate at time zero (to) in mcf/d

b = the hyperbolic exponent, dimensionless

Di = the initial decline rate, 1/yr

t = elapsed time from to in years

The coefficients b and Di can be determined by using fitting algorithms with model output rate data

This function is commonly used in the oil and gas industry to predict future well production by best-fitting actual production data to the function and then extrapolating the expected production through time.

The vented mine decline curve generated by the conceptual model described above is initiated at 100 percent of the subject mine's average emission rate while active, while the sealed mine's curve is initiated at some fraction of that emission rate. The total volume of methane emitted will be similar, but it will occur over a longer period of time. Accordingly, this methodology treats the emissions prediction from a sealed mine in a similar manner to emissions from a vented mine, but using a lower initial emissions rate that depends on the perceived degree of sealing. The CFD simulator was again used with the conceptual abandoned mine model to predict the decline curve for inhibited flow. **Figure 4** below shows examples of these decline curves (from the above reference EPA document). This figure shows a set of decline curves for several cases with different degrees of sealing for a mine in the Black Warrior Basin. The emission rates are normalized to the average emission rate of the mine of interest. **Figure 4** illustrates how the initial rate of decline decreases as the degree of sealing (percent sealed) increases.
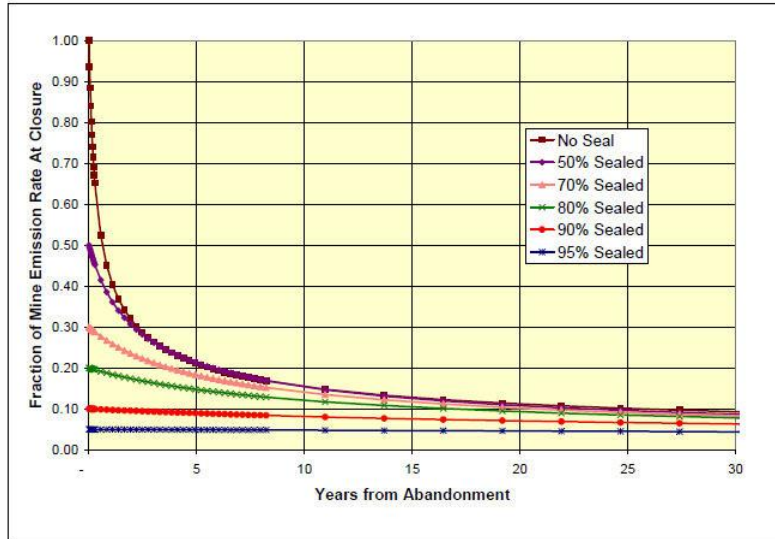
Figure 4: Emission Rates at Different Sealing %

Unfortunately, no measurements of diffuse emissions are available to calibrate the sealed mine emission rate calculations. Therefore, the decline curves shown in **Figure 4** were used to select the high, mid-range, and low values for sealed mine emissions. As the figure illustrates, the difference in emission rates between an unsealed mine and a 50% sealed mine is insignificant after a year of closure. However, significant differences are seen in the fractional emission rates between cases for 50%, 80% and 95% closure achieved for sealed mines. Thus, these values were selected as the low, mid, and high range values for the extent of mine sealing, respectively. The low, mid and high curves were used with Monte Carlo simulation to provide a range of probable outcomes and to provide uncertainty bounds for the EPA GHG inventory estimate.

For the purposes of the AMM protocol the 80% curve or mid-case EPA curve is selected. As is noted in **Figure 5**, an 80% sealed assumption leads to conservative emissions reductions compared to assuming no mine seal.
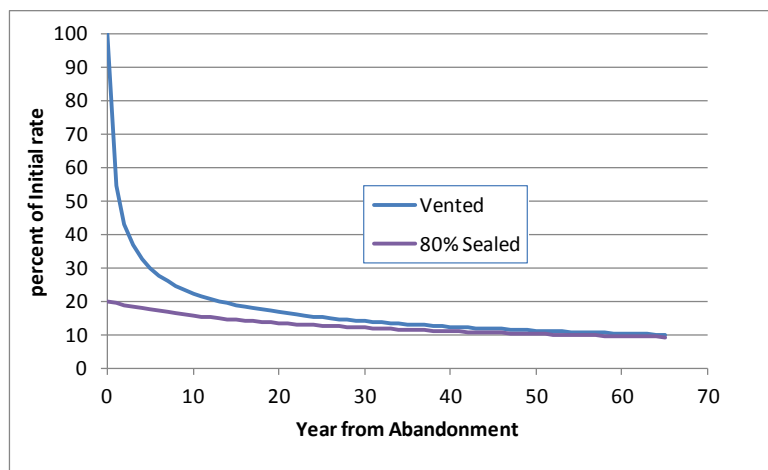
Figure 5: Emission Rates at Different Sealing %

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Examples of Baseline and Actual AMM Emissions

The examples of baseline emissions and project emission destruction show that the baseline estimates are conservative when related to project emissions destruction. This is primarily related to the project's installation of vacuum compression. This is done to accelerate the production of the gas for economic reasons. Significantly higher rates are achieved by this method because of the large free gas volume within the void that can be produced at high rates before the lower rate methane desorption from the remaining coal takes over. Although production may be significantly greater than the baseline, only the AMM productions up to the baseline volumes are credited as emission reductions. The accelerated production by generating under vacuum not only improves project's end use economics, but will significantly reduce future AMM emissions even after the project ceases. As can be seen in **Figure 6,** the baseline emissions (blue line) are much less than the actual AMM gas production (red line), leading to conservative emission reductions.
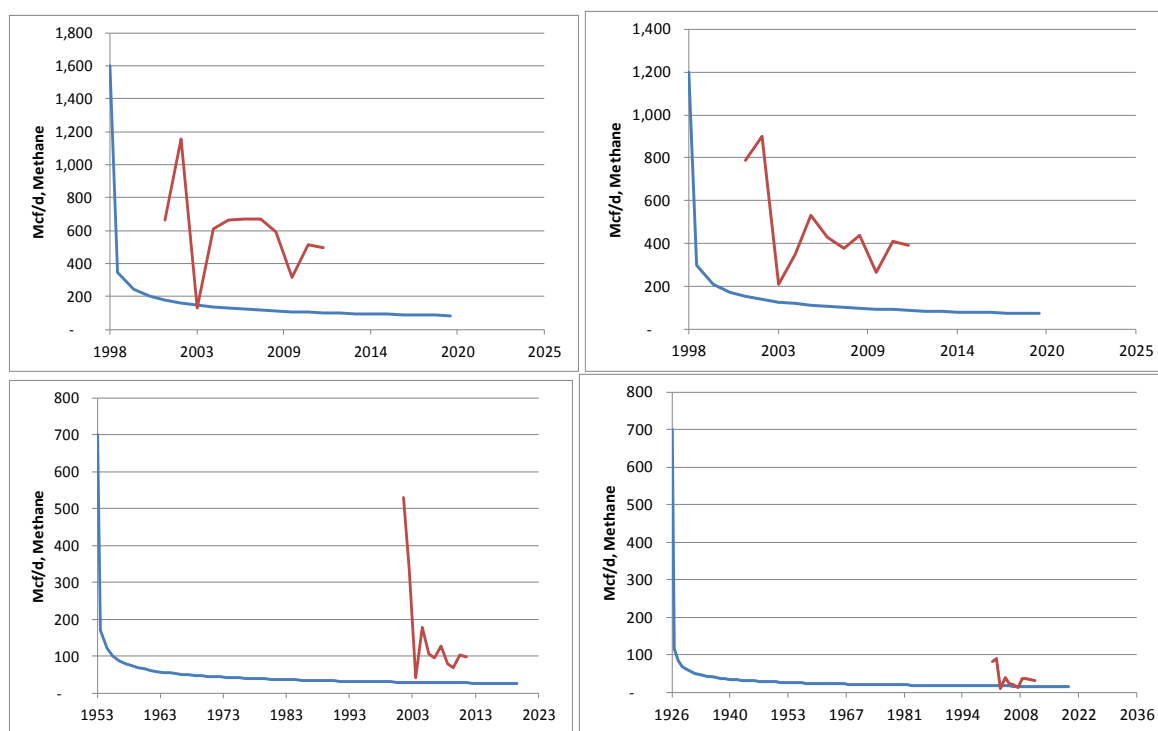
Figure 6: Baseline Emissions Compared to Produced AMM

Maximum Adoption Potential

While there are approximately 645 abandoned coal mines emitting methane (500 closed since 1972), not all mines present a project opportunity. Many of the mines did not have attractive project opportunities as active coal mines, and therefore would not offer AMM recovery opportunities unless the individual mine was part of a large network of mines in close proximity to each other. Typically, AMM emissions (and potential project size) represent just of 10-15% of active mine emissions.

It is estimated that approximately 105 of the 645 abandoned mines hold opportunity for viable methane recovery projects. The 105 mines identified represent approximately 65% of the total U.S. AMM emissions. Of the 105 mines, 38 mines have existing projects in place. New project potential exists at the remaining 67 abandoned mines located in nine states including: Pennsylvania, West Virginia, Virginia, Ohio, Kentucky, Indiana, Illinois, Colorado, and Utah. Estimated annual methane recovery from these 67 mines is approximately 5.8 Bcf or 2.3 million metric tons CO_2e (representing approximately 32% of total AMM emission in the U.S.)

Threshold Level of Activity Penetration

In 2011, 16 AMM utilization projects in the U.S. recovered about six Bcf of AMM from 38 abandoned mines (representing approximately 7% of abandoned mines and 33% of total AMM emissions in the U.S.). In some instances an AMM project is a combination of methane recovered from multiple mines. Nearly all current projects are located at the largest and gassiest mines available, or in areas where AMM can be aggregated from several abandoned mines into a single project. As noted above, 33% of all AMM emissions in the U.S. have been captured by only 16 projects. Two of the largest developers of coal mine methane (CMM) at active mines (Consol Energy and Walter Energy) typically continue their CMM projects after mines have been closed, since gas infrastructure is already in place and their mines are in close proximity to ongoing CMM recovery operations. However, their projects represent only 12 of the 38 abandoned mines with recovery projects. More often, the original coal mine company has left the property, and AMM projects are developed by small oil and gas businesses.

In 2011, the 16 existing AMM projects used three types of methane utilization/destruction technologies; 13 pipeline sales projects, two electric power generation projects and one flaring project.

Financial Viability

There are numerous hurdles to overcome in order to produce a financially viable abandoned mine methane recovery and use project.

Resource Issues

Abandoned mines are a uniquely unconventional source of natural gas. While the technology required to recover natural gas produced from intact coal beds (coal bed methane or CBM) has matured over the past 25 years and has spread worldwide, the recovery of methane trapped in abandoned coal mines has only been developed in a few countries in Europe and in the United States. The reason this resource is not more fully developed is primarily economic and the nature of the resource is one reason.

- The gas within the workings of abandoned mines is primarily methane (usually between 60% and 80%), but also is composed of significant quantities of nitrogen and carbon dioxide and may also have oxygen and hydrogen sulfide. All of these non-hydrocarbons must be removed to low levels in order for the gas to be sold to commercial pipelines.
- The quantity of available gas depends on how much has already escaped to the atmosphere either through diffuse emissions from fissures in the overburden or through or around seals placed in original ventilation shafts or other boreholes that were placed into the mine for mining

operations (such as utility boreholes). The size of the mine will directly bear on the quantity of the available resource as well.

- Ground water flooding in the mine can significantly reduce the volume available for recovery both by reducing the volume of the void space and blocking the desorption of additional gas from the coal. Flooding can also compartmentalize the gas in the mine requiring additional boreholes to access non flooded pockets of gas.

Recovery Issues

Recovering the AMM for commercial use can be problematic for several reasons:

- Locating the most advantageous drilling location
  - Wells must be located where they are most likely to access the most gas, which are usually main roadways that intersect with other roadways that in turn can access mined out areas.
  - Land leases for drilling and government permits are required and can be time consuming and expensive. This also goes for any pipelines or utilization equipment that needs to be installed.
- Vacuum pumps are normally used in order to recover an economically viable amount of methane after the initial pressure in the void is depleted, usually occurring within two or three years. These are expensive units and often use the produced AMM for fuel, making less available for sale.
- If the gas is to be sold, gas treatment to remove water and other containments as well gas compression necessary for treatment and sale.

Market Issues

As with all natural gas sources, a market for the gas or the power that may be produced, must be available at prices that allow for a profit especially given that AMM is a high operating cost resource. Some market issues include:

- Low price of natural gas. The price of natural gas has ranged between $3.00 and $5.00 per million BTU over the past two years and is currently around $4.00/MMBTU. It is expected that this will be the range over the foreseeable future.
- Low wholesale price of electricity. The price of electricity in the mid-west has been close to $30/MWhr, which translates closely to $3.00/MMBTU. The ability to connect to the power grid can also be problematic in certain areas of the country.

It has been found in other studies that power generation can be economically preferable to gas sales at these prices because internal combustion engines can take gas at low pressure, removing the need for high pressure compression. In addition, internal combustion engines can use a low BTU gas, which eliminates the need to remove non-hydrocarbon contaminants, excluding H_2S and water. Therefore, the pro forma economic analysis found below was performed using power generation as the end use of the AMM.

Pro Forma Economic Analysis

Production data from eight abandoned coal mines in the mid-continent area of the U.S. was used as the basis for this analysis. All of these mines have been producing AMM (off and on) for the last eleven years. These mines have been networked with pipelines to a central processing facility where contaminants were removed, and the gas is compressed and sold to a commercial natural gas pipeline. Due to the fact that capital and operating cost of this project is proprietary information, the following analysis was performed as if each mine were a standalone power generation project. The U.S. EPA Coalbed Methane Outreach Program (CMOP) cash flow model was used for this analysis[3].

All cost parameters were held constant for all mines except the average methane rate over the 11 years and the number of wells drilled into the mine. The average methane rate affects the size and hence the cost of the power generation equipment and the number of wells affects the overall capital and operating cost. Attachment 1 at the end of this section is an example of the economic input/output for Mine 7. **Table 1** shows the results of the discounted cash flow analysis run at $50/MWhr for all eight mines.

This demonstrates that under current economic conditions the generation of power at an abandoned mine will likely not meet a required investment hurdle rate of return. For future AMM projects to initiate additional economic incentives are needed, such as income from emissions reduction credits.

	Cumulative CH4, Mcf	Average Rate Mcf/d	Number of Wells	10% NPV	IRR	MWe
TABLE 1: RESULTS OF PRO FORMA ECONOMIC ANALYSIS						
Mine 1	644,719	160	4	-$463,000	1.76%	0.53
Mine 2	1,217,012	303	3	-$320,000	6.60%	1.09
Mine 3	136,110	34	2	-$269,000	-5.58%	0.11
Mine 4	149,283	37	1	-$159,000	-8.40%	0.12
Mine 5	1,788,274	445	4	-$407,000	6.77%	1.47
Mine 6	1,220,941	304	3	-$325,000	6.30%	1.01
Mine 7	1,836,718	457	3	-$295,000	7.64%	1.51
Mine 8	2,344,659	584	5	-$489,000	7.02%	1.93

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[3] http://www.epa.gov/cmop/resources/cashflow_model.html